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U.S. DEPARTMENT OF ENERGY
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TESSERACT: dark matter detection with transition edge sensors and multiple targets

Xinran Li
Physics department, Lawrence Berkeley Laboratory
The TESSERACT collaboration

12/03/2022
DBD23, Waikoloa Village, Hawaii

TESSERACT

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The TESSERACT project

- Direct search for low-mass dark matter
- Transition Edge Sensors (TESs) with Sub-EV Resolution And Cryogenic Targets
- Polar crystal -- SPICE
- Superfluid helium -- HeRALD

Recent progress

- Dark matter search with a 10g, 10eV threshold silicon detector
- ~1eV threshold detector
- Low energy excess events
- Low Tc, low stress films
- Proof-of-principle HeRALD detector operation

Coming up next

- Two-channel devices
- Second helium detector for calibration
- Underground experiment preparation

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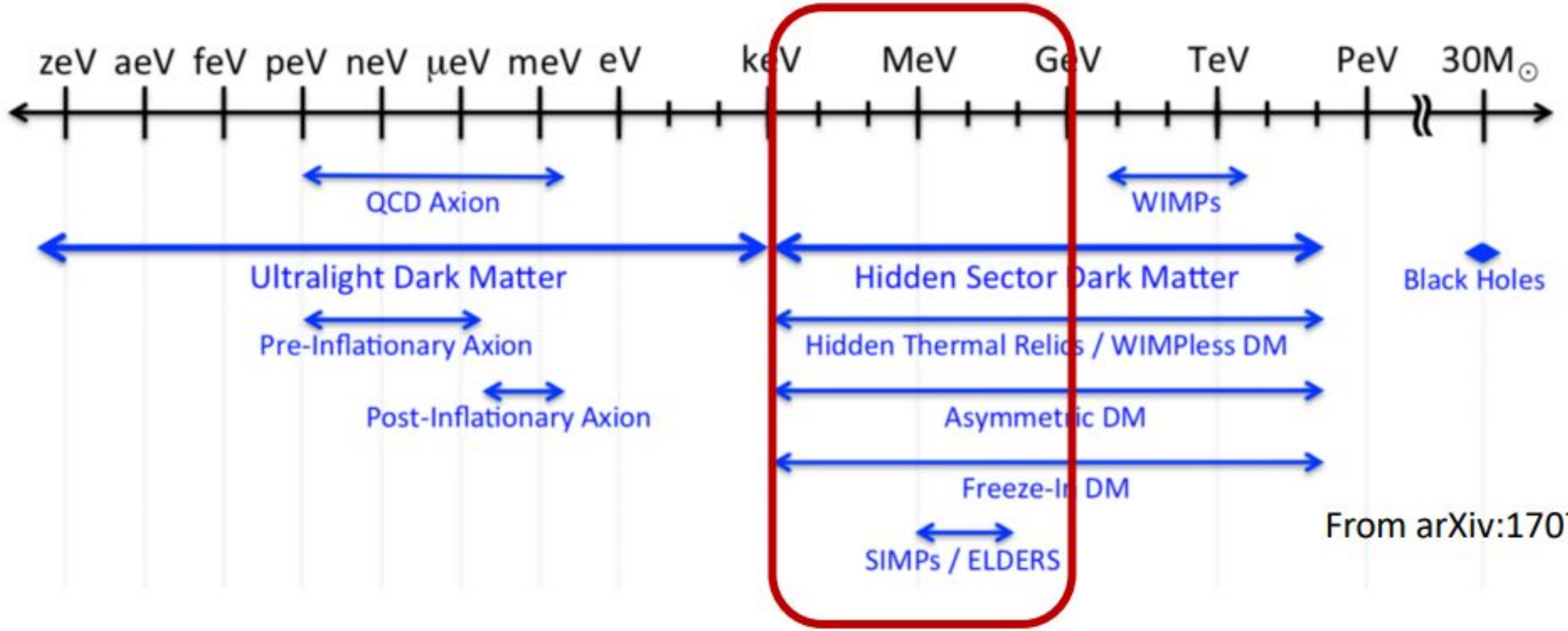
The TESSERACT project

Direct detection for low-mass dark matter

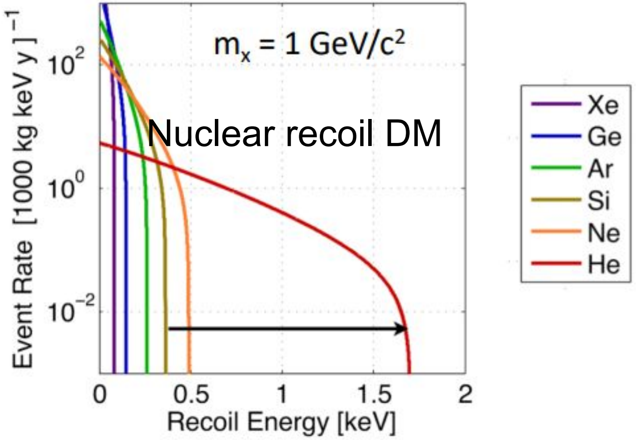


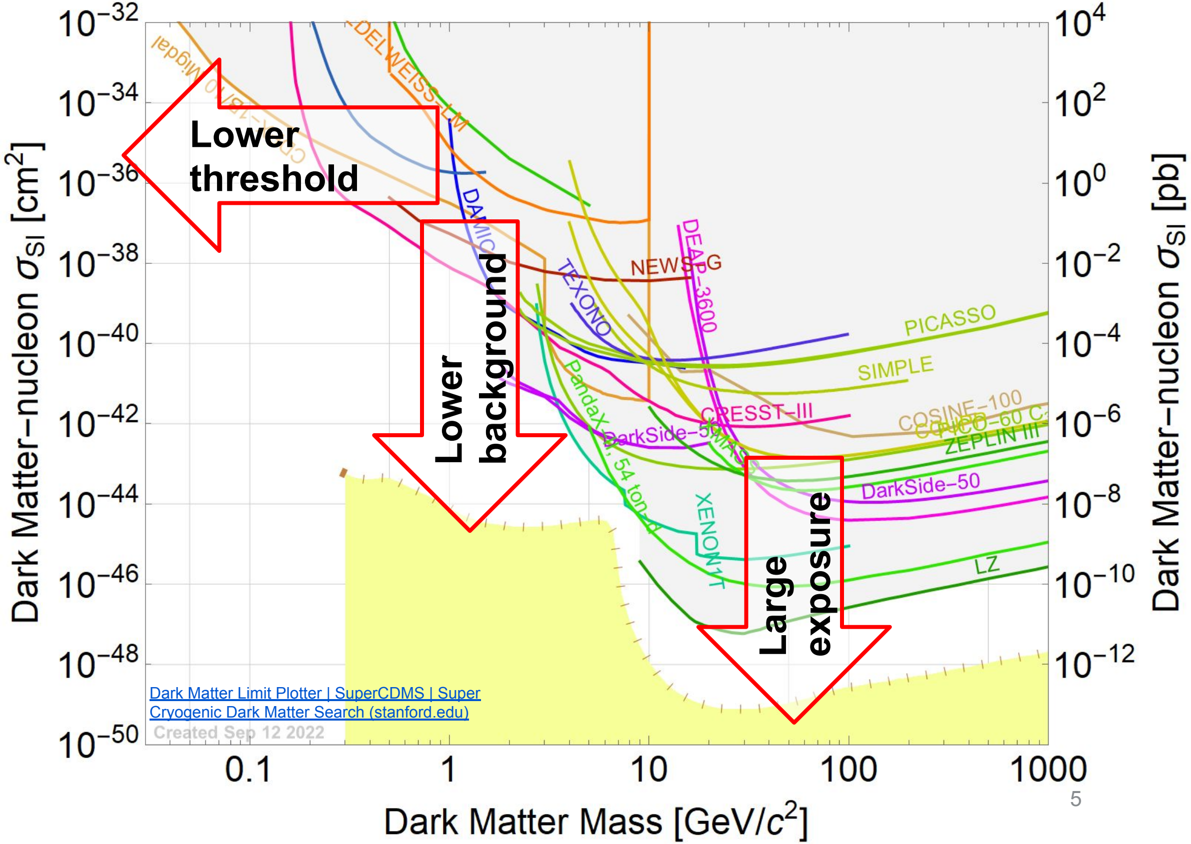
From arXiv:1707.04591

Direct detection for low-mass dark matter

Low threshold

Target with light element





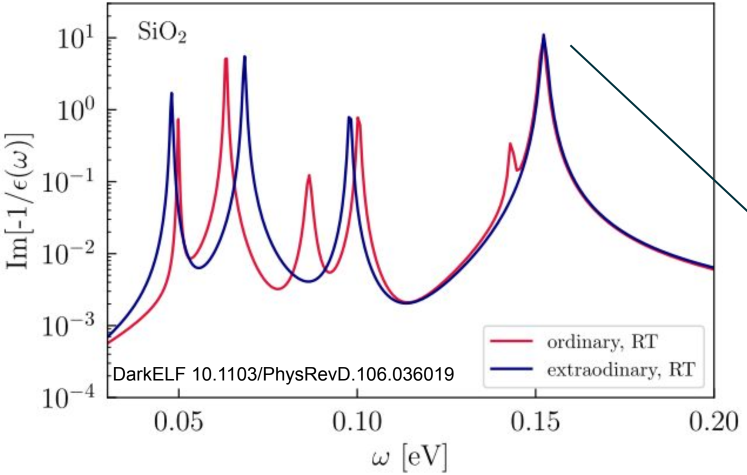
Direct detection for low-mass dark matter

Low threshold

Target with light element

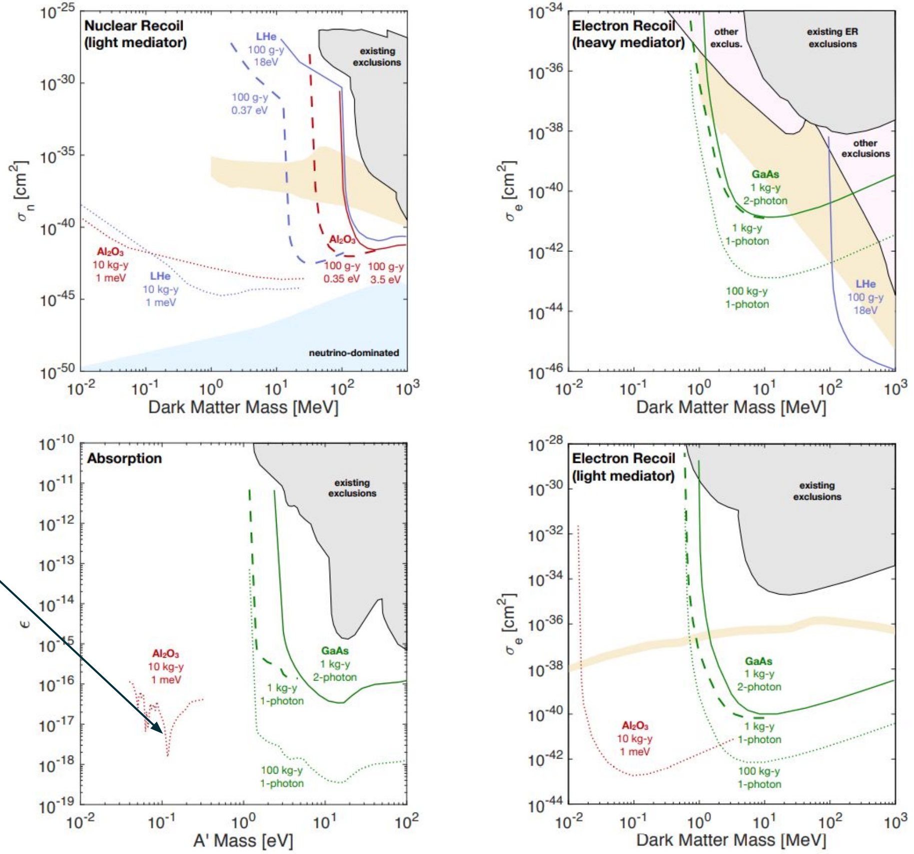
Polar crystal: optical phonons, dark photon coupling.

Dark photon coupling



DarkELF 10.1103/PhysRevD.106.036019

Snowmass2021 - Letter of Interest
[The TESSERACT Dark Matter Project]



Direct detection for low-mass dark matter

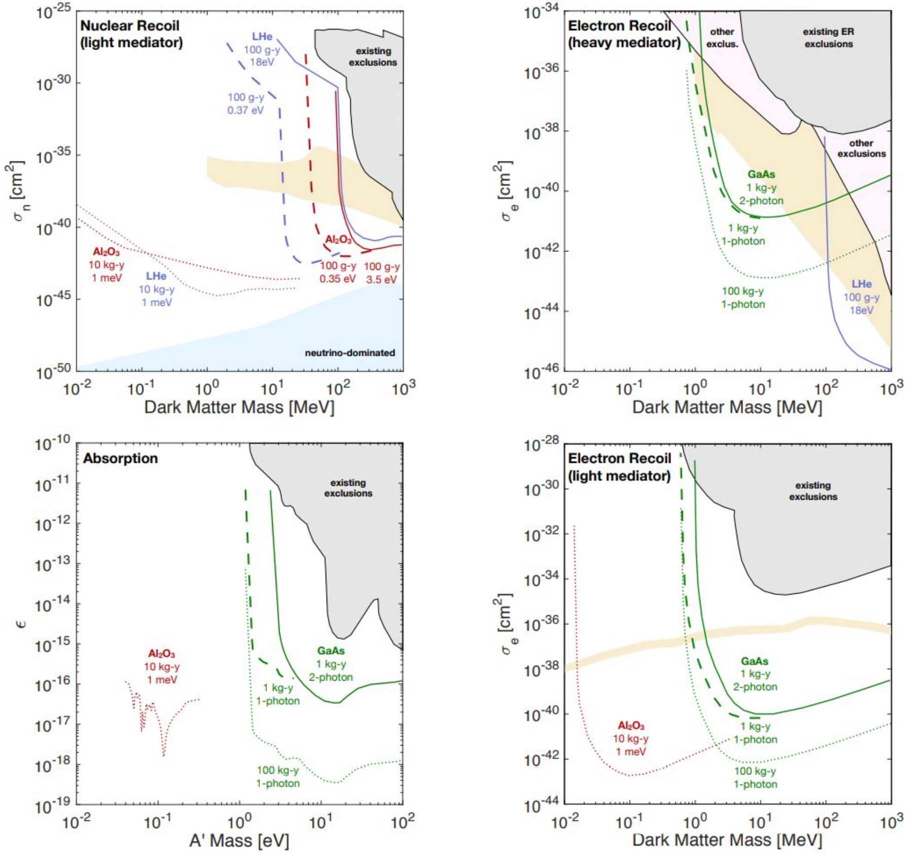
Low threshold

Target with light element

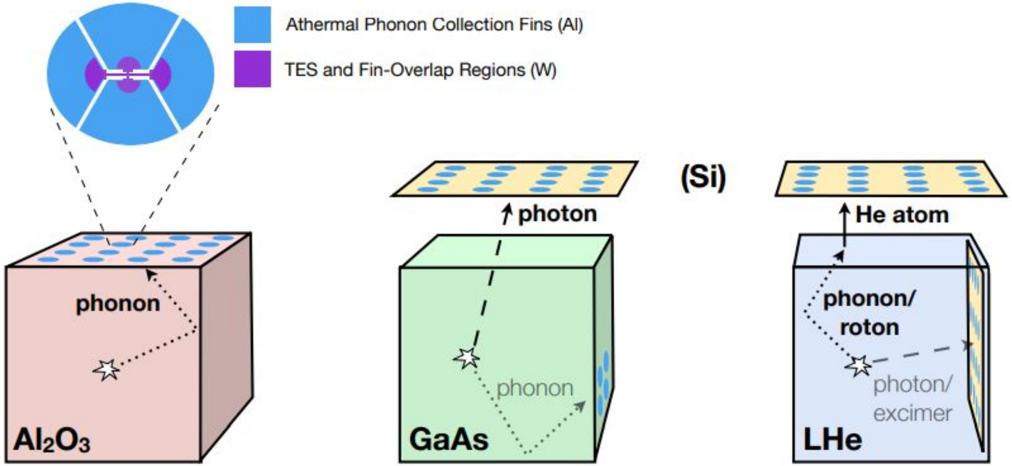
Polar crystal: optical phonons, dark photon coupling.

→ **Develop a low-threshold (sub-eV) sensor for multiple cryogenic targets: TES based athermal phonon sensors!**

Snowmass2021 - Letter of Interest
[The TESSERACT Dark Matter Project]



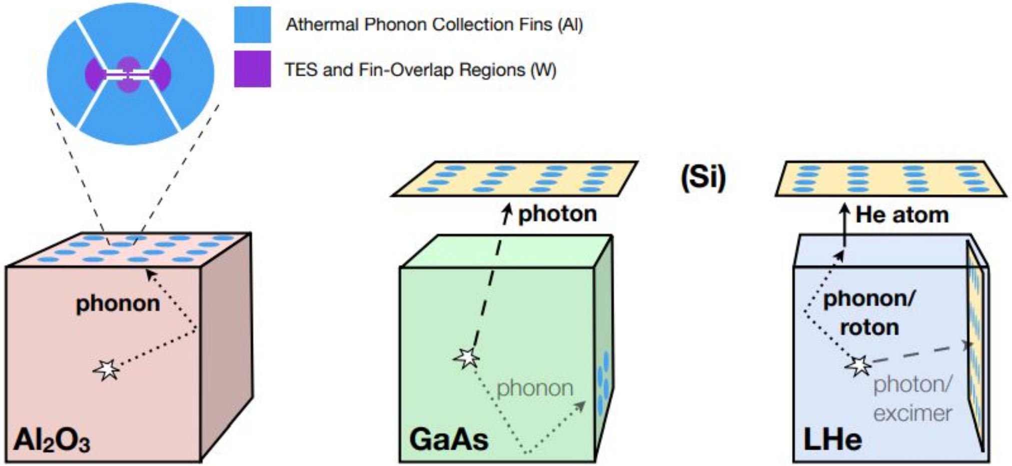
TESSERACT & Athermal phonon sensor



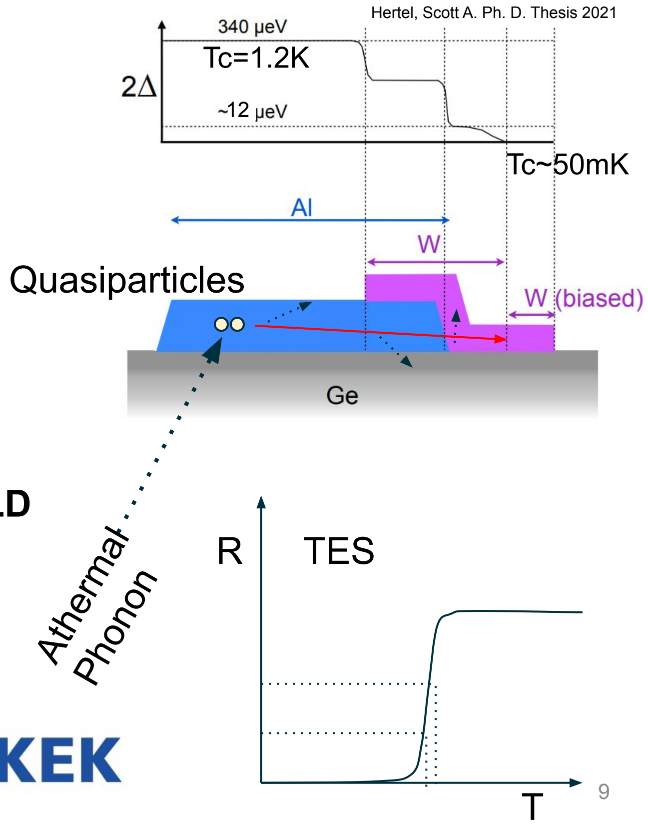
Polar crystals: **SPICE**

Superfluid helium: **HeRALD**

TESSERACT & Athermal phonon sensor



Polar crystals: **SPICE** Superfluid helium: **HeRALD**



TESSERACT: SPICE

Use polar crystals as targets.

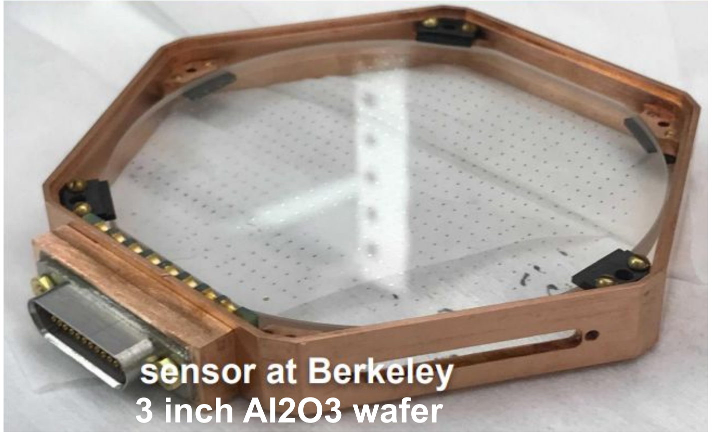
- Al_2O_3
- GaAs

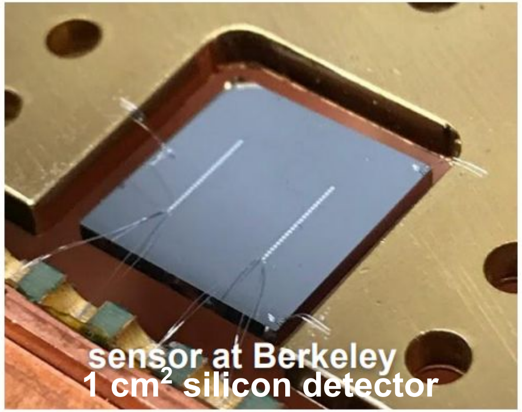
GaAs is also a great cryogenic scintillator, can use photons to do background discrimination.

Currently use silicon substrate for fast R&D:

- Tune TES film Tc to achieve sub-eV energy threshold. 55mK Tc → 20mK Tc
- Understand noise and background.

GaAs and Al_2O_3 R&D in parallel.





TESSERACT: HeRALD

Use superfluid helium as target.

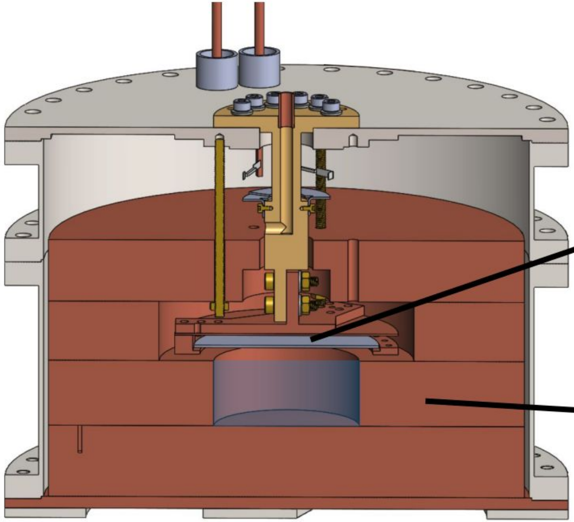
Use silicon photon detector as sensor.

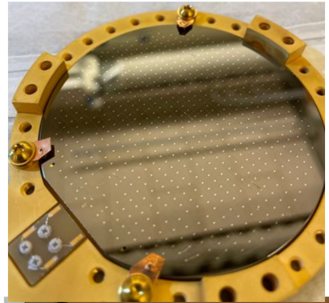
- 16eV scintillation photon
- Quantum evaporation from rotons and phonons

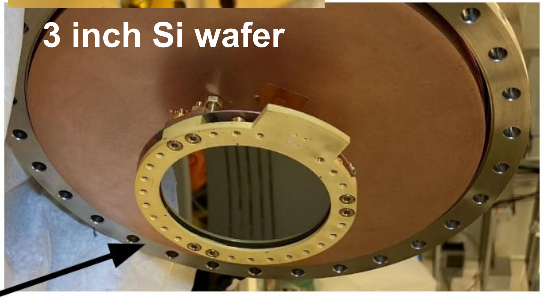
Currently focus on understanding the detector response

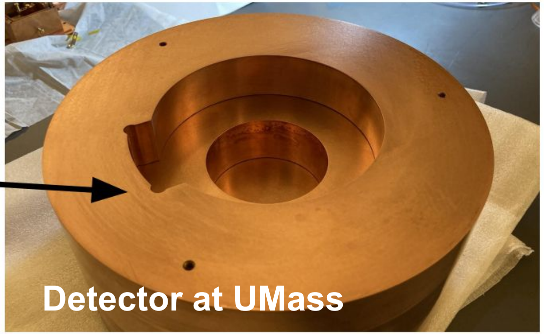
- Roton detection efficiency
- Quantum evaporation gain
- Superfluid helium response

arXiv:2307.11877









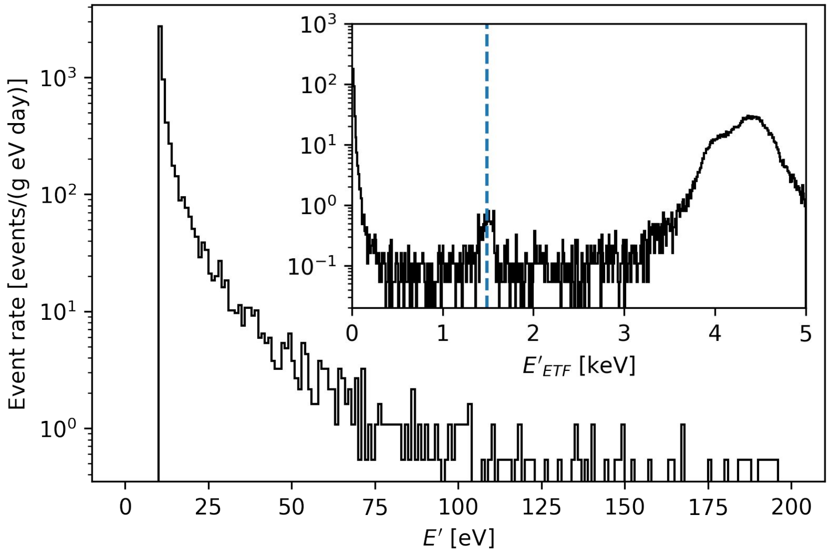
Recent progress

Dark matter search with 10g, 10eV threshold Si detector

Same detector for the HeRALD readout.

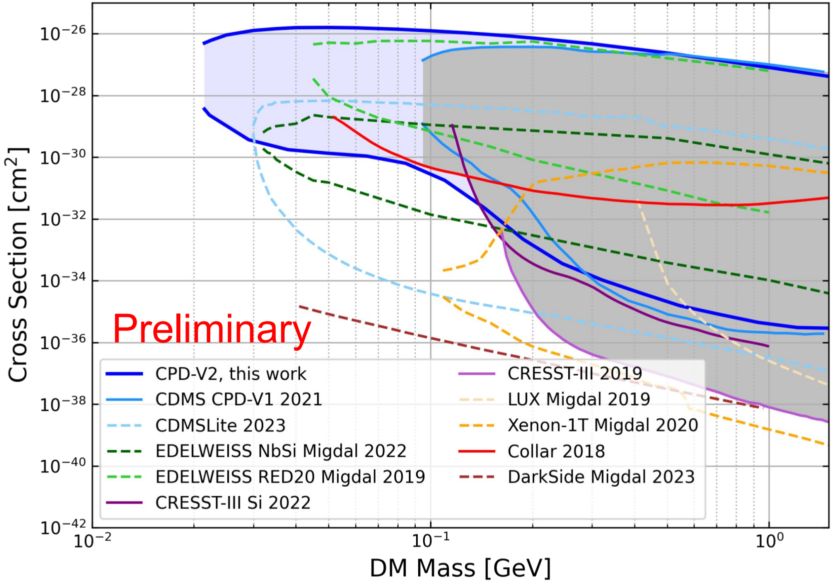
Large spectrum: Energy region of interest

Inset: High energy region with 1.48keV Al k-alpha calibration peak



Preliminary limit on nuclear recoil dark matter.

Low-energy reach competes with Migdal effects.



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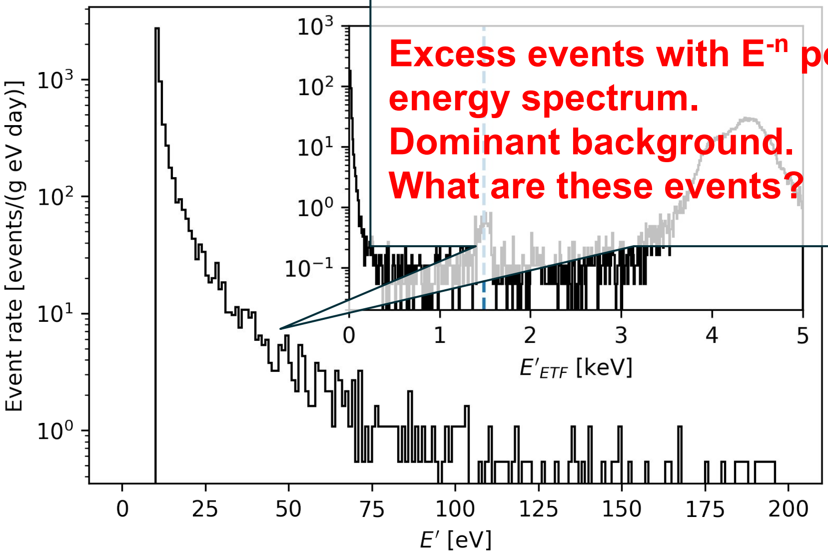
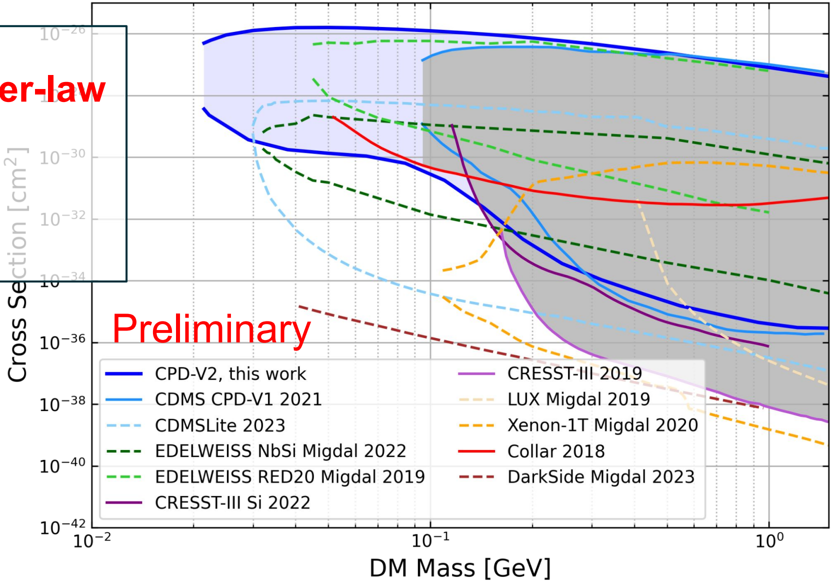


Excess events with E^{-n} power-law energy spectrum.
Dominant background.
What are these events?

Preliminary limit on nuclear recoil dark matter.

Low-energy reach competes with Migdal effects.



~1eV threshold detector

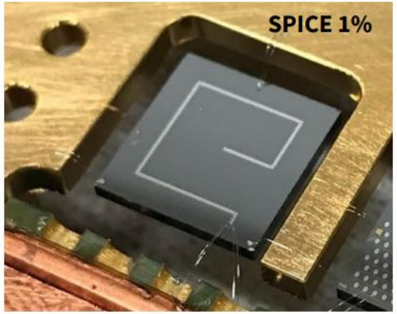
Reduce target mass. Reduce surface coverage.

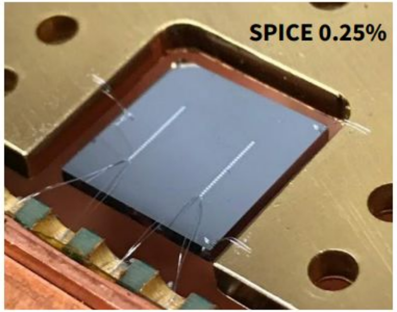
1cm^2 1mm thick silicon detectors.

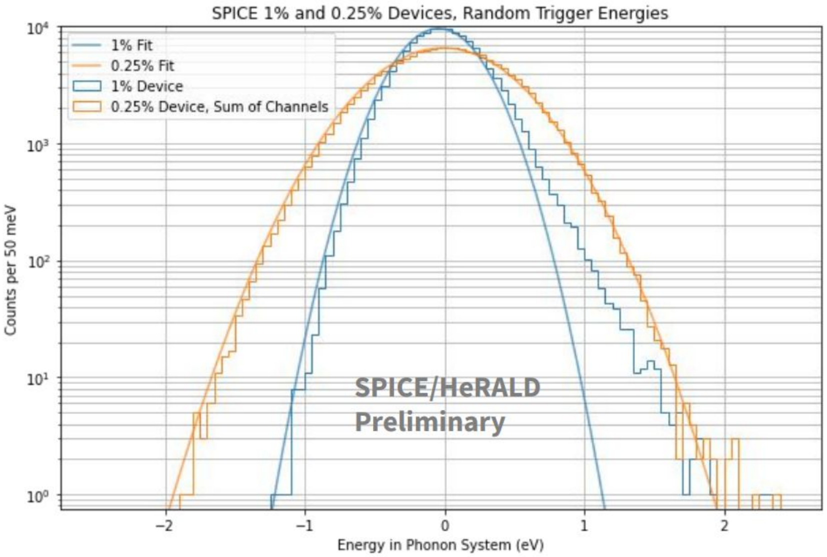
Free-hanging from wire bonds to reduce stress.

SPICE 1%: ~273 meV (sigma) energy resolution in phonon system

SPICE 0.25%: ~460 meV (sigma) energy resolution in phonon system







CPAD Talk 2023 (stanford.edu)

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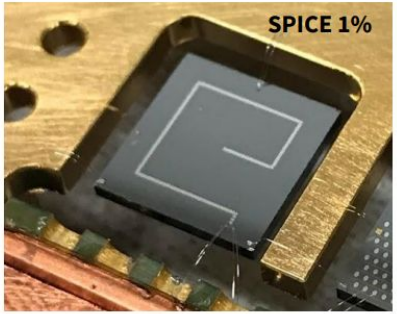
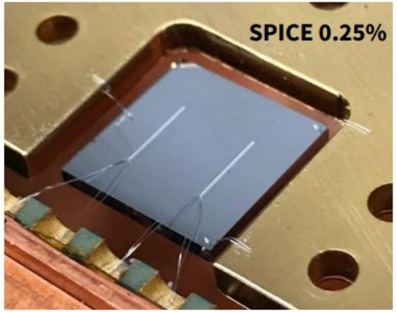
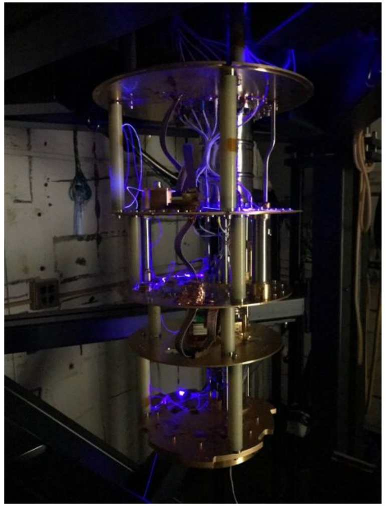
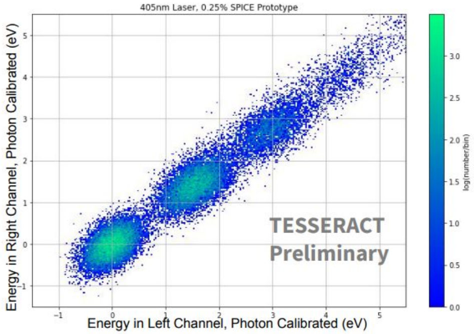
Energy calibrated with optical photons!

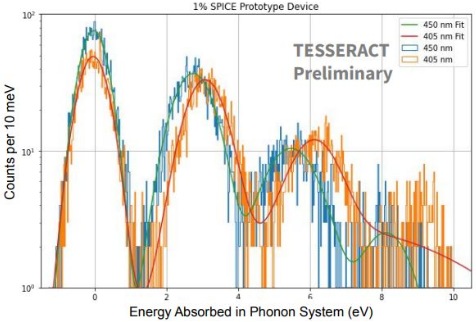
450nm and 405nm











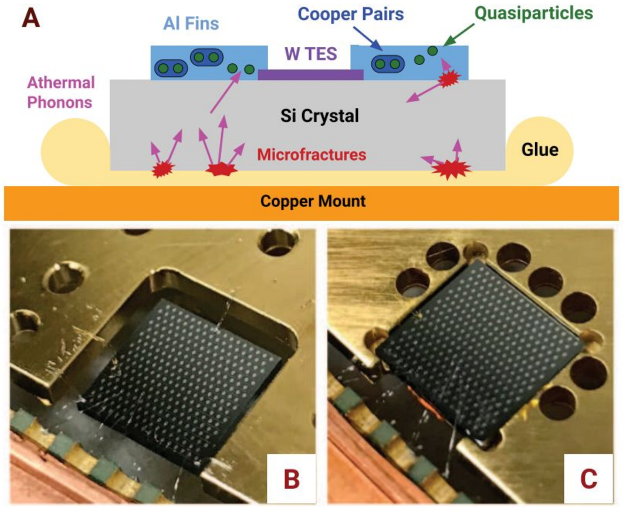
[CPAD Talk 2023 (stanford.edu)]

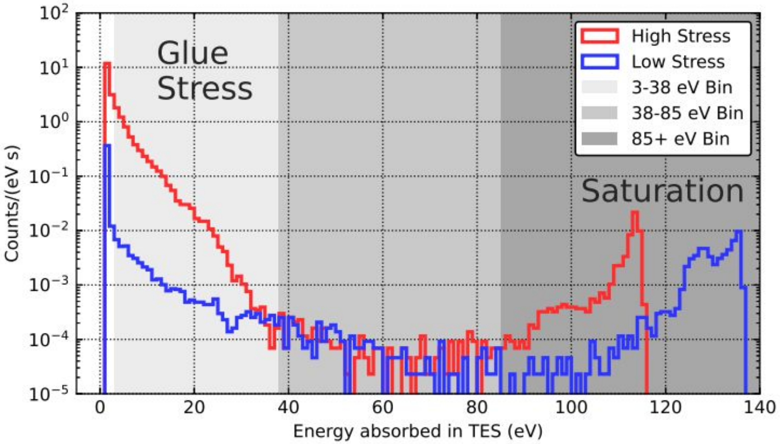
Low energy excess events

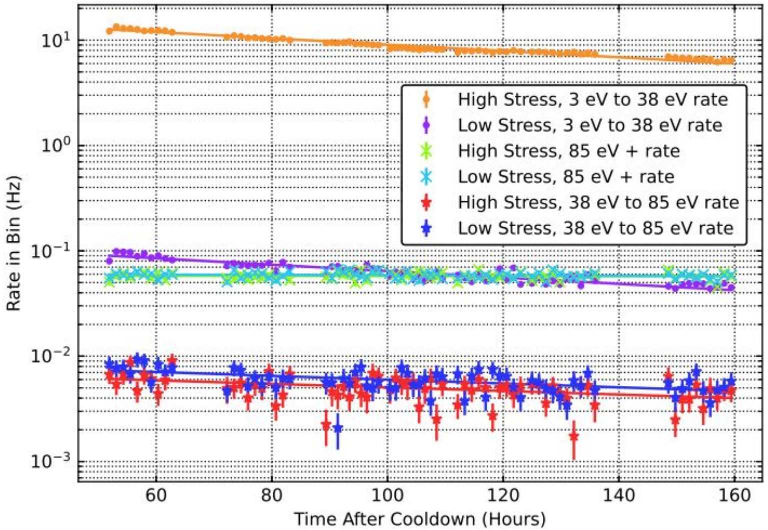
Stress related low energy events.

High stress mounting introduce higher rate.
Rate decays exponentially with cold time.
Events of same spectrum and decay observed in many experiments. Non-ionizing.

→ **Hanging device + low stress film.**







arxiv:2208.02790

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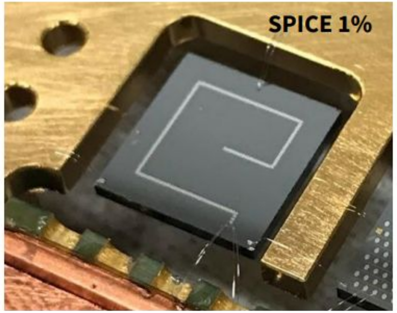
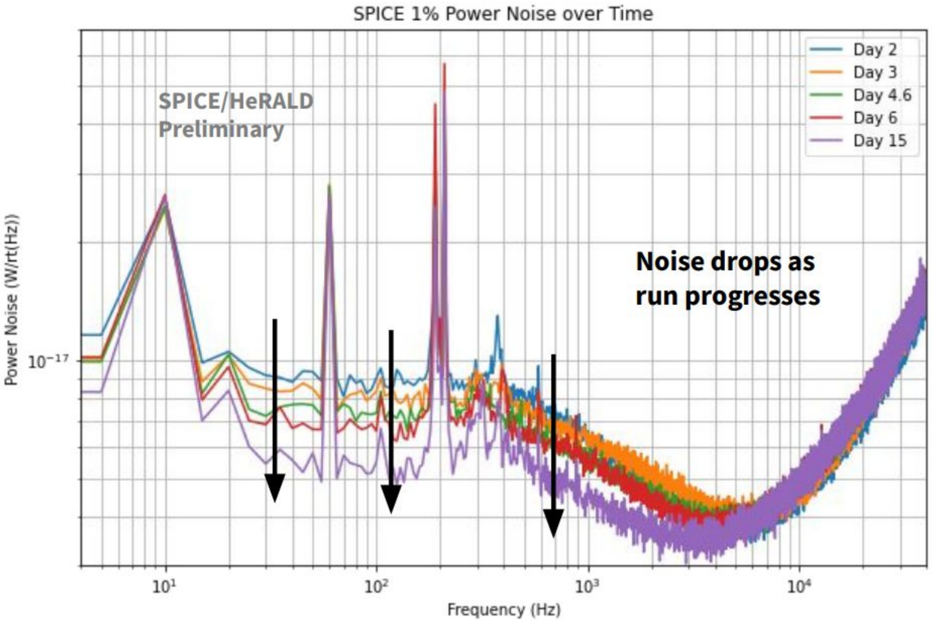
Rate decays exponentially with cold time.
Events of same spectrum and decay observed in many experiments. Non-ionizing.

→ **Hanging device + low stress film.**

The low coverage device's energy resolution improves over time as the LEE rate decreases!

- **The LEE spectrum extends to below threshold.**
- **The LEE also prevent us reaching the theoretical energy resolution.**





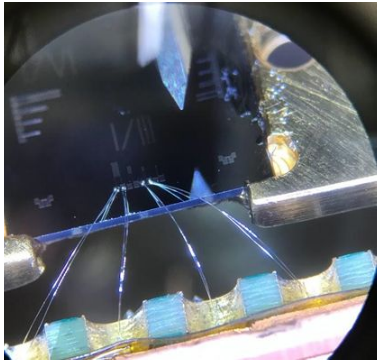
[CPAD Talk 2023 (stanford.edu)]

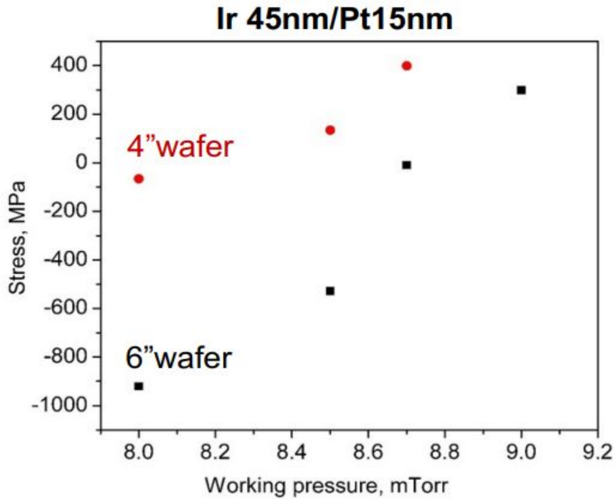
Low stress low Tc films

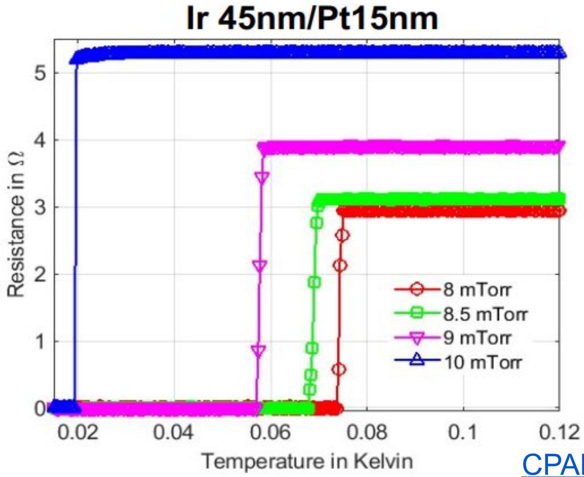
First attempt with tungsten film.
Low Tc achieved. Not low stress.

Good results from Ir/Pt bilayer samples from Argonne National Laboratory.

TES fabrication finished. Tests on going!







CPAD_2023

Proof-of-principle HeRALD detector operation

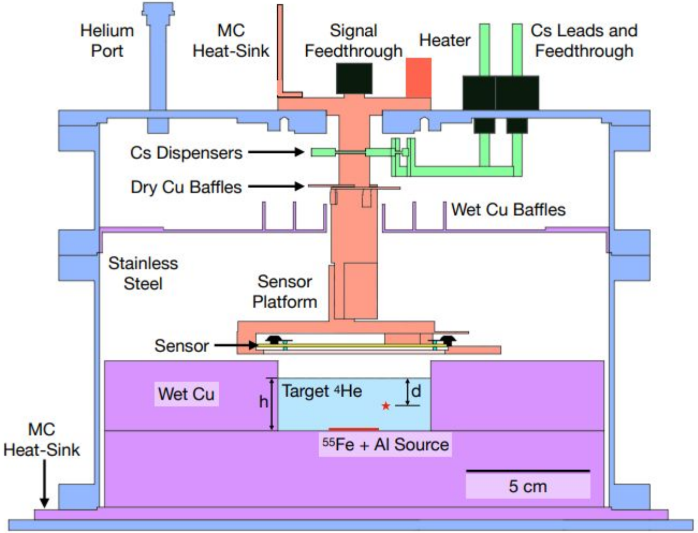
Cs superfluid helium stoper demonstrated.

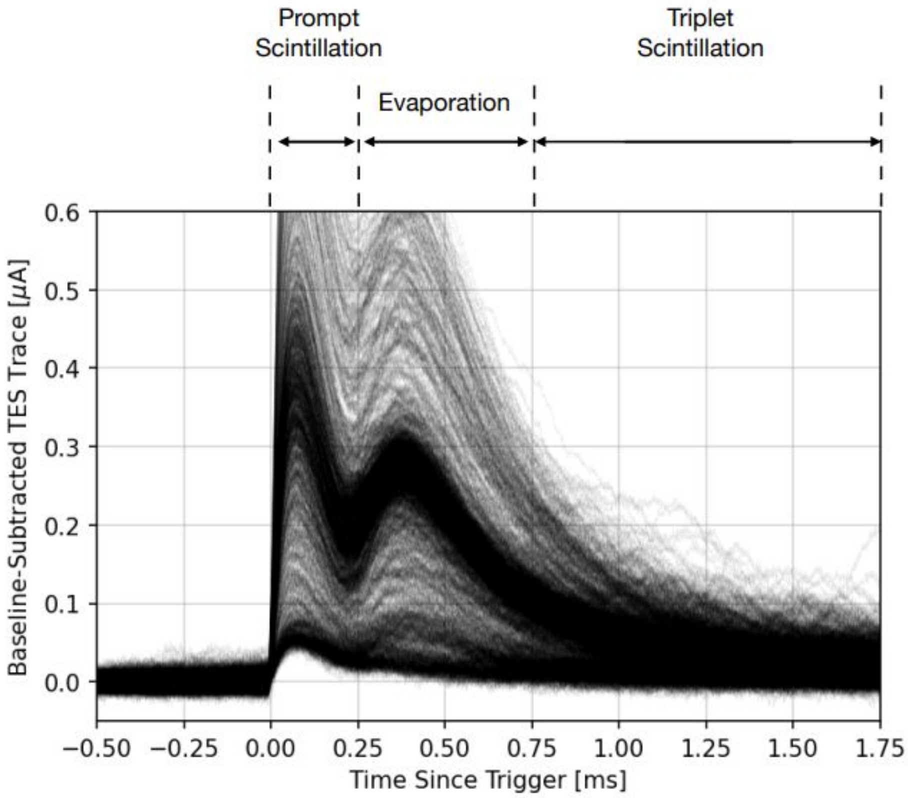
Photon and quantum evaporation signals observed.

145eV energy threshold.

Ready to explore very interesting helium physics!

[arxiv: 2307.11877](https://arxiv.org/abs/2307.11877)





Proof-of-principle HeRALD detector operation

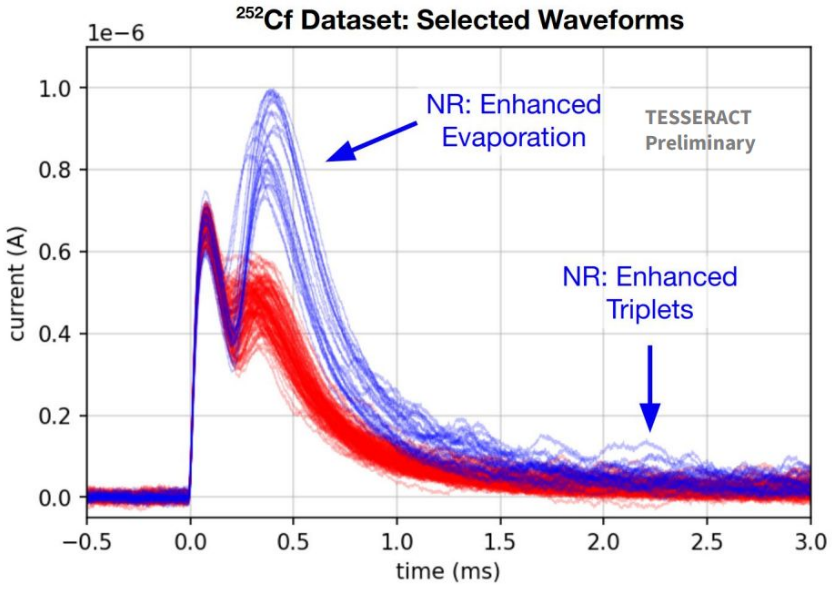
Cs superfluid helium stoper demonstrated.

Photon and quantum evaporation signals observed.

145eV energy threshold.

Ready to explore very interesting helium physics!

Clear discrimination between electron recoil and nuclear recoil.



Red - ER

Blue - NR

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Coming up next

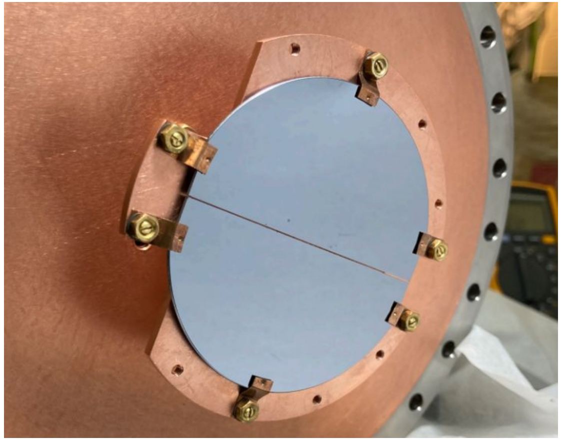
Two channel devices

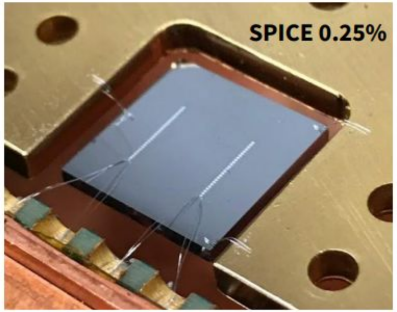
Path to LEE background rejection

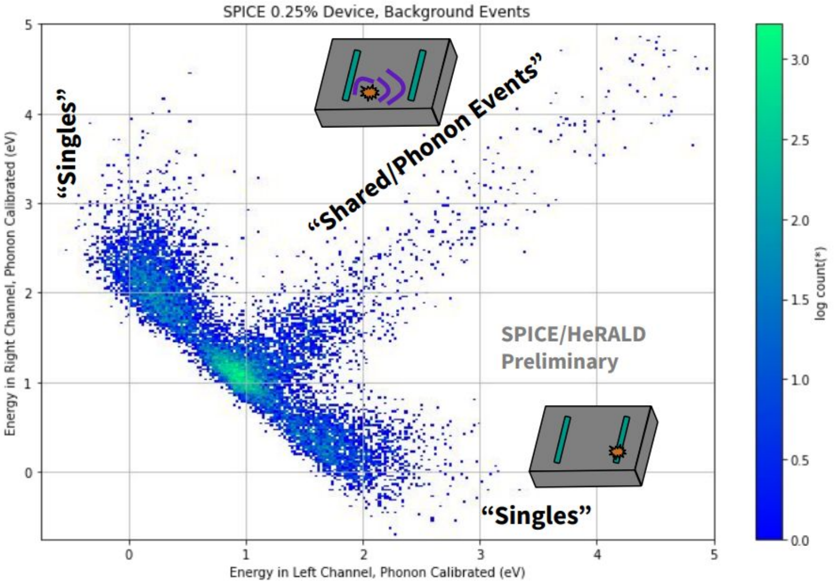
Helium readout with split CPD

Two TES channels on one silicon substrate

Need to improve triggering algorithm

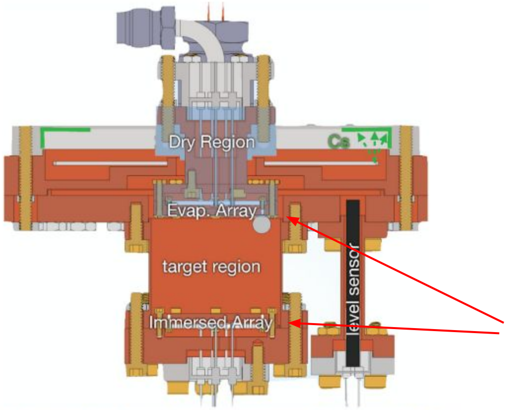


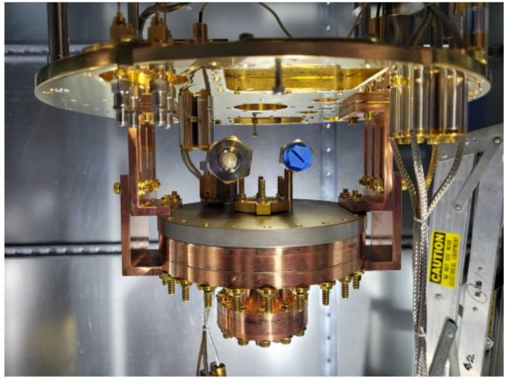


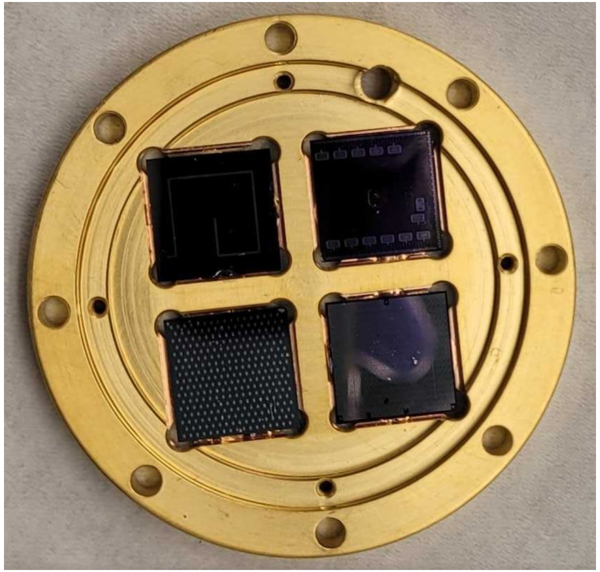


Second HeRALD detector at LBL

- Improved design for better Cs deposition.
- 2 by 2 readout arrays on top and bottom.
- Helium electron recoil and neutron recoil calibration.
- Quantum evaporation efficiency and gain calibration.





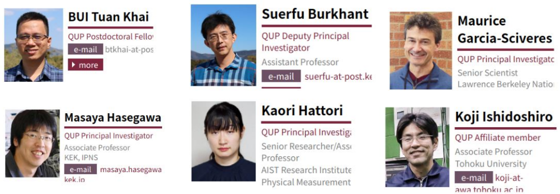


Underground experiment preparation

Underground labs

Photos for reference

From https://www2.kek.jp/qup/en/member/



US - SURF
Space ready in 2025
Planning for 2 payloads

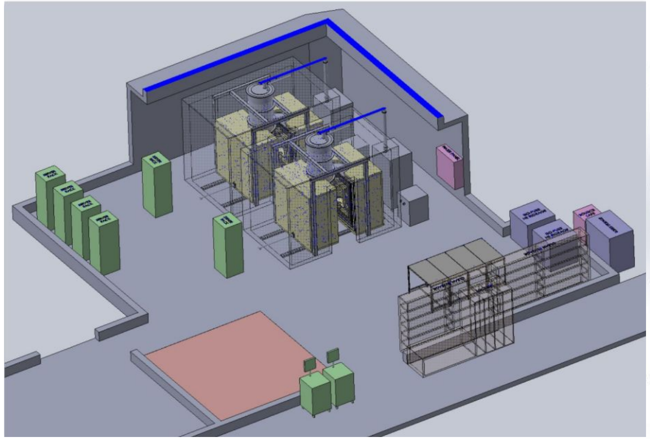
France - Modane - LSM

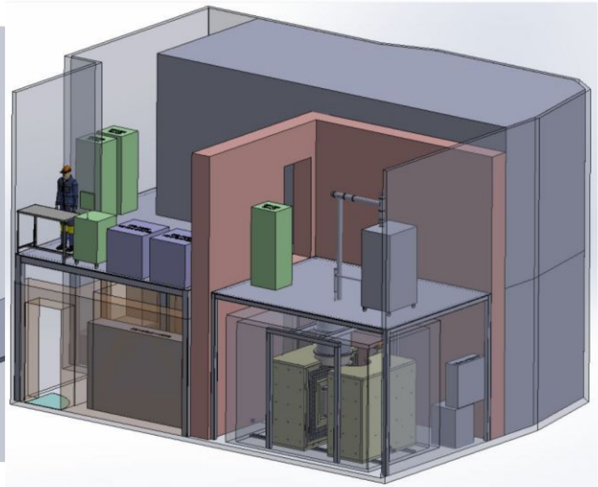
Project presented to French community since Oct 2022.

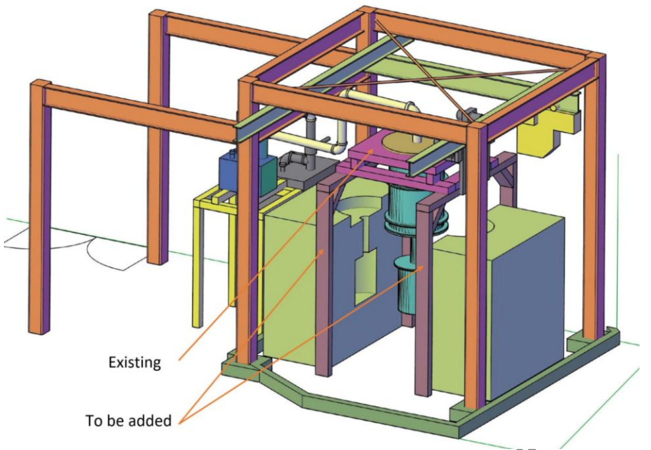
Planning for 1~2 payloads.

Japan - Kamioka
Commissioning: ~mid 2024.

Science payload:
~10g-yr exposure
~20eV threshold.





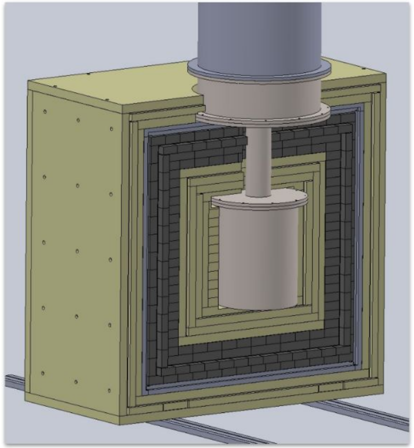


Underground experiment preparation

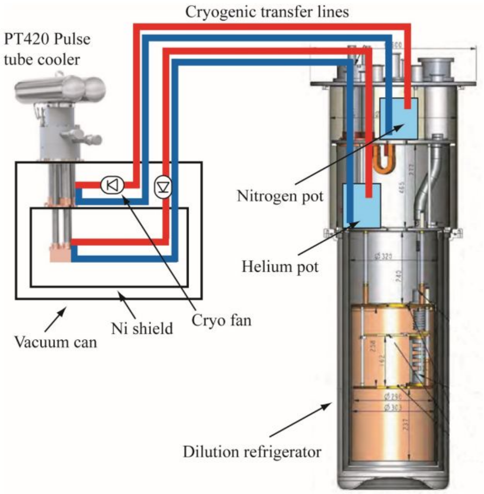
Low background environment

1 DRU shielding

Simulation + engineering design



Zero vibration cooling



EMI/RF/IR shielding

Parasitic noise power from EMI/RF/IR is the limiting factor to go to lower energy threshold.

- Improve fridge RF tightness.
- Improve detector holder IR tightness.
- Filter EMI/RF/IR from TES bias.

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Conclusion

- TESSERACT has a strong collaboration and we are building up momentum.
- The goal is to explore the large parameter space from 1GeV to 1keV dark matter mass with various target materials.
- 10g, 10eV silicon device obtained world-leading results.
- Results from ~1eV threshold device on the way.
- Successfully demonstrated superfluid helium detector with film stopper and quantum evaporation signals. Next iteration detector will be ready soon.
- Reduce background:
    - Reduce film stress.
    - Reject single events in two-channel devices.
- Simulation and engineering design for underground experiments goes in parallel.

Thank you!
Questions?

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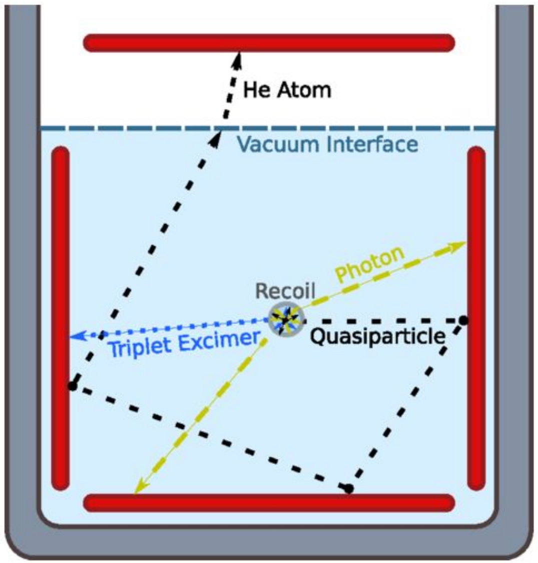
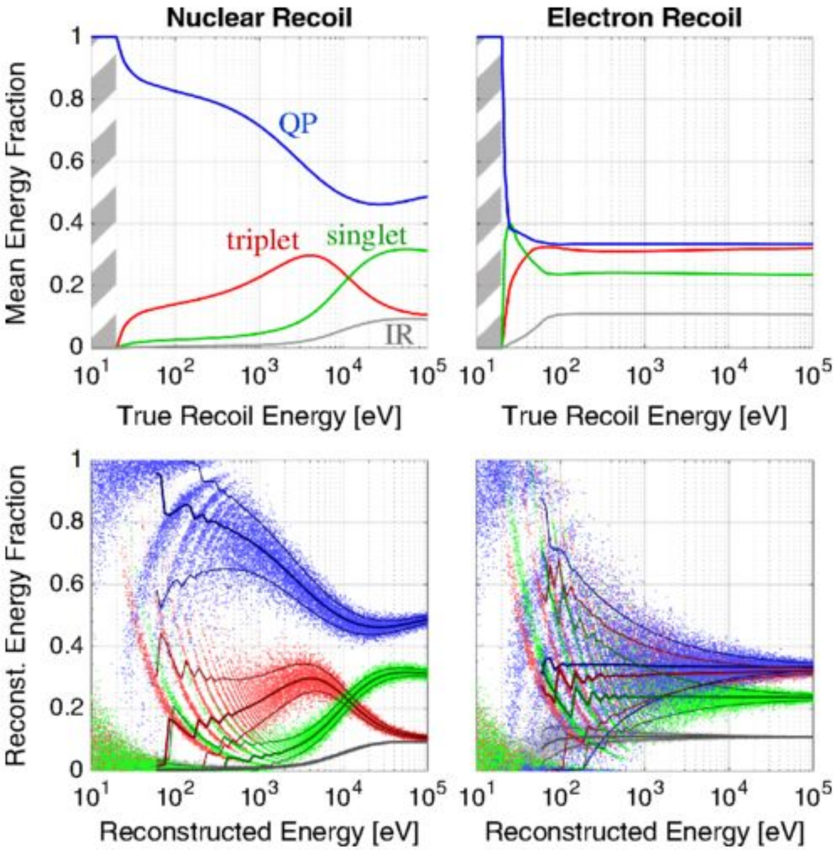
Back up

HeRALD detector concept and helium response

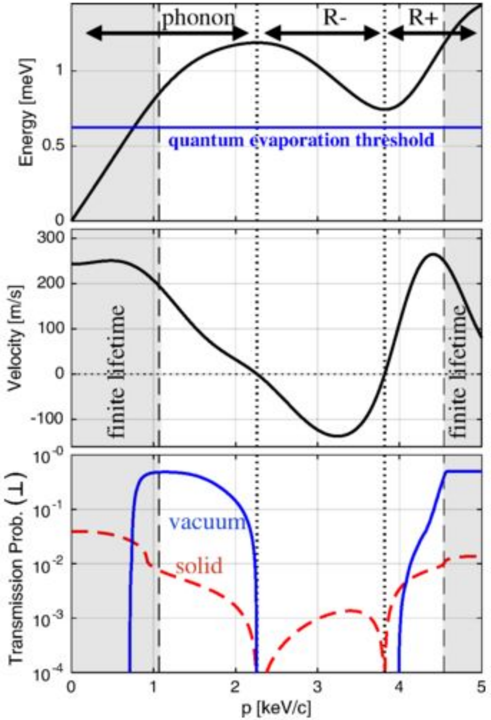
[Phys. Rev. D 100, 092007 (2019)](#)

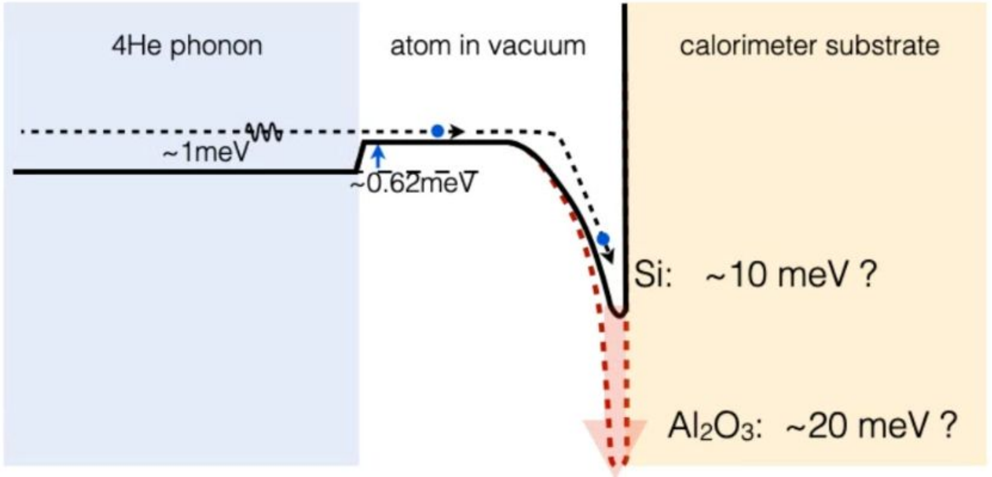




HeRALD detector quantum evaporation

Phys. Rev. D 100, 092007 (2019)





Amplification by surface adsorption

Athermal phonon sensor energy resolution

TES noise is limited by the thermal fluctuation noise of the thermal link G between the TES and the bath.

$$\sigma_E \sim \frac{\sqrt{4k_b T_c^2 G(\tau_{collect} + \tau_{sensor})}}{\epsilon_{collect}\epsilon_{sensor}}$$

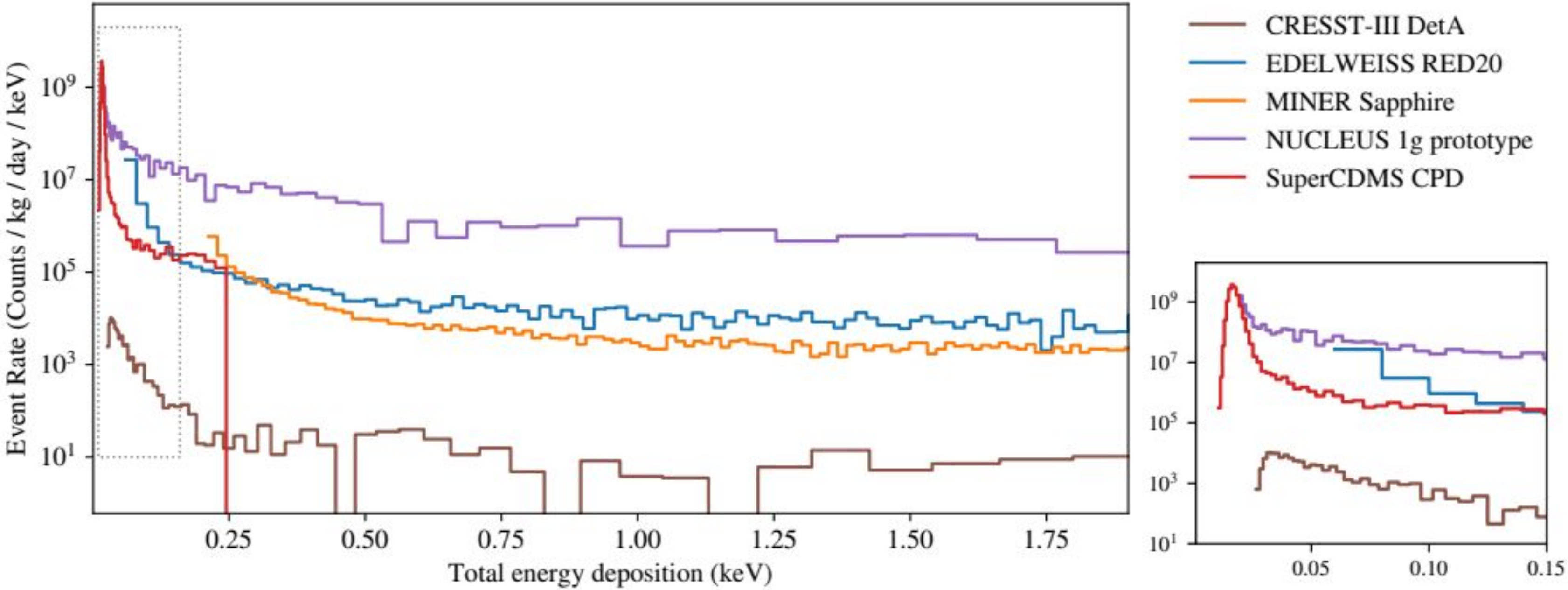
Thermal phonon TES sensor: $\tau \sim C_{detector}/G \rightarrow \boldsymbol{\sigma_E \sim T_c^{3/2}}$

Athermal phonon sensor: Thanks to extra freedoms from the phonon collection fins, $\tau_{collect}$ can be engineered to match τ_{sensor} (the time scale of electrical-thermal feedback) $\rightarrow \boldsymbol{\sigma_E \sim T_c^{3}}$

- **Lower Tc**
- **Optimization of phonon and quasiparticle collection efficiency.**

Caleb Fink Thesis

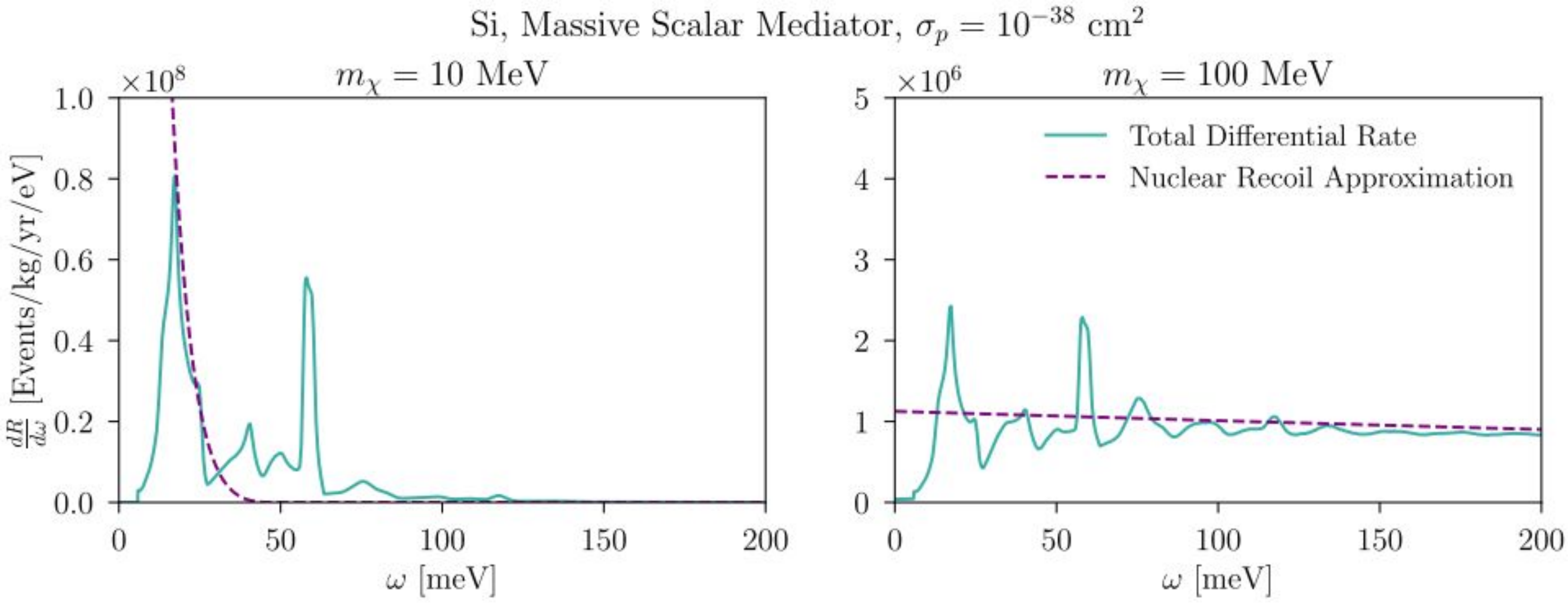
LEE event spectra from various experiments.



[arxiv: 2202.05097](https://arxiv.org/abs/2202.05097)

Multi-phonon creation in crystals

Gains additional sensitivity at sub-eV



DOI: 10.1103/PhysRevD.106.036019

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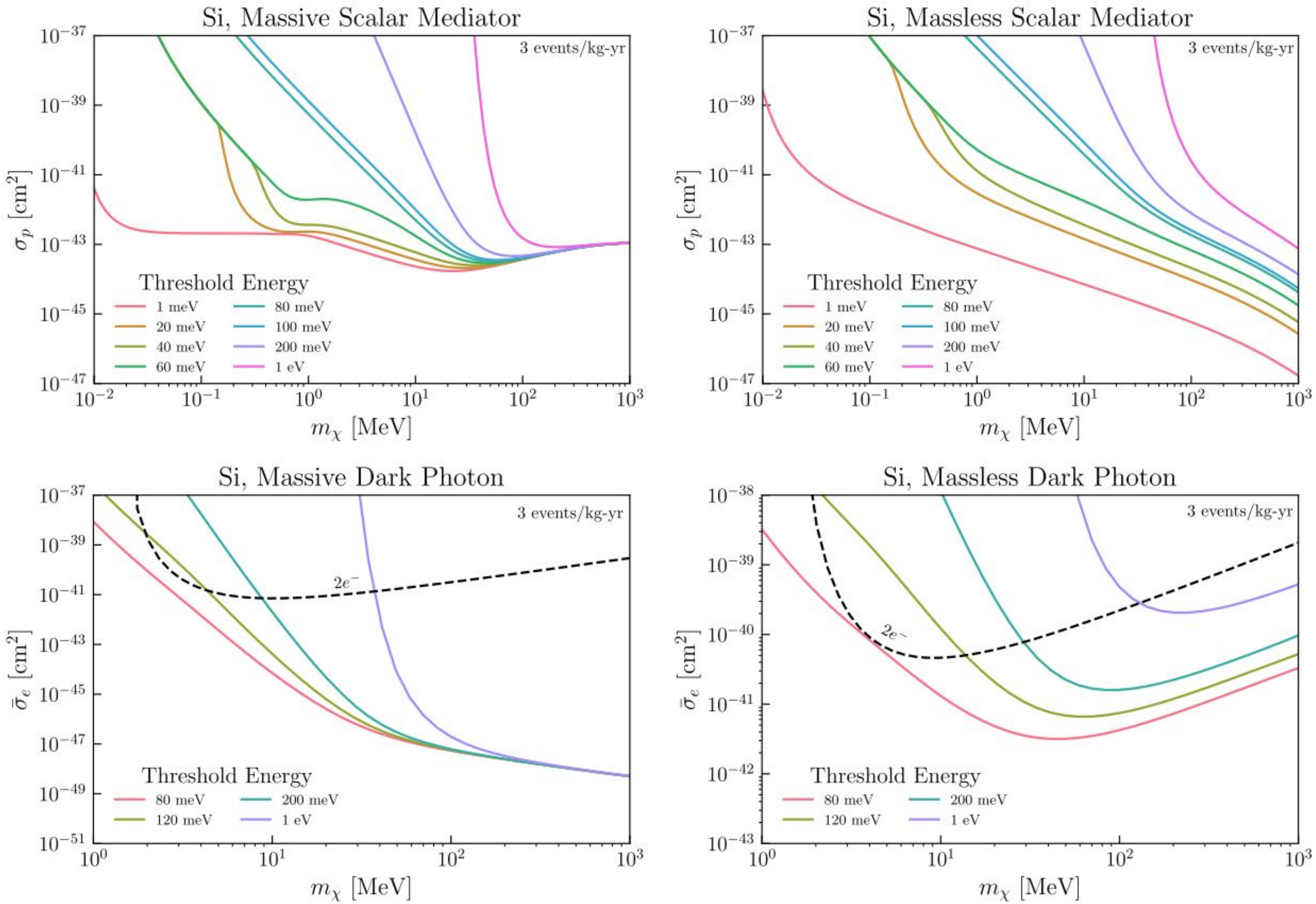
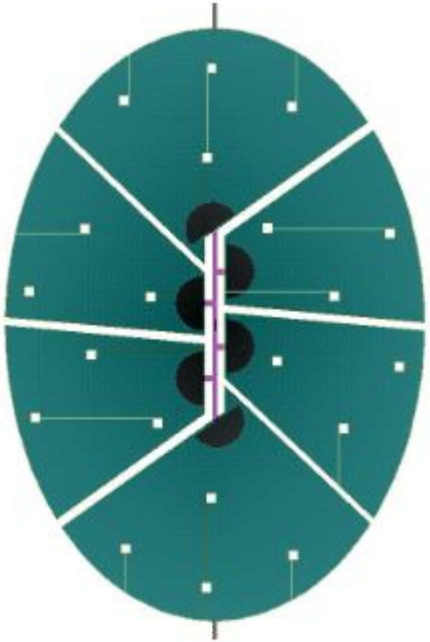
Multi-phonon creation in crystals

Gains add



CPDv2 design



TES length	140 µm
TES Thickness	40 nm
TES width	2.5 µm
n_{fin}	6
Fin Length	150 µm
Fin Thickness	600 nm
Al/W Overlap	20 µm
N_{qet}	673
Active Surface Area	0.68%
Passive Surface Area	0.18%
R_n	200 mΩ
QP Abs Efficiency	52%
Tot Efficiency	18% (Simulated)